SCIENCE FOR GLASS PRODUCTION

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THE EFFECT OF FLAME LENGTH ON EXTERIOR HEAT EXCHANGE IN A GLASS MELTING FURNACE WITH HORSESHOE-SHAPED FLAME

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The topicality of studying heat and mass exchange in a glass-melting furnace with horseshoe-shaped flame is substantiated. The main requirements on advisable flame length in this type of furnace are formulated. The need for jointly solving the exterior and interior heat-transfer problems is demonstrated. The results of calculating temperatures of the gaseous medium, the roof, and the glass melt surfaces depending on the flame length are given. It is established that based on the set of conditions, the recommended length of the flame can be taken equal to the furnace length. The extent of the intense combustion zone (visible part of the flame) in this case is approximately 0.7 furnace length.

At present the main thermal plant for melting container glass is a regenerative tank furnace with a horseshoe-shaped flame. Its design has not undergone significant changes during the past 20 years. At the same time, the engineering and economical parameters of foreign furnaces have reached a rather high level. It is sufficient to note that the efficiency of contemporary furnaces exceeds 50%. This is largely due to the evolutionary upgrade of furnace elements. This primarily concerns the designs of the melting tank, burners, regenerator, etc. A high furnace efficiency implies efficient thermal insulation using high-quality refractories. Furthermore, a high-efficiency furnace requires state-of-the-art control systems and a careful attitude to the quality of initial materials and batch quality.

The effect of the majority of the above factors on furnace parameters can be estimated not only qualitatively, but quantitatively as well, including the analysis of the thermal balance items. The design specifics of the main furnace components appear understandable and reproducible. Our knowledge of the glass-melting process and the furnace design appears quite extensive, consequently, we could assume that reaching a high efficiency is just the matter of financial resources. Unfortunately, the actual practice demonstrates that copying a successful furnace design, as a rule, does not produce results adequate to the prototype. The point is that the technical efficiency of a furnace depends on a set of interrelated factors, where the furnace design is only one of significant components.

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A significant aspect in the performance of a glass-melting flame furnace is setting up heat-transfer processes in the working space and in the melting tank. As the chemical energy of fuel is the main source of heat generation, a rational implementation of the combustion process (the flame) is one of the most essential problems of thermal engineering in glass melting. According to the method of V. G. Lisienko [1], four main parameters of a flame have the most significant effect on heat and mass transfer in the glass-melting furnace, namely the length, the radiation, velocity, and other aerodynamic characteristics of the flame, as well as the flame position with respect to the heated surface (glass melt). The above flame parameters, in turn, are integrated and, as a rule, interrelated values.

The present paper gives the results of the calculation of heat and mass transfer depending on the flame length. The flame length in applied studies is usually accepted as the extent of the fuel combustion zone, in the end of which chemical underburning on the flame axis is equal to $q_3 = 0.02Q_{\mathrm{w}}^1$ (Q_{w}^1 is the lowest working heating capacity of fuel). The appropriateness of this formula is due to the asymptotic fuel combustion and the possibility of instrumental monitoring of the flame length. The specified value q_3 corresponds to a carbon oxide content in combustion products equal to approximately 0.5%.

The problem of the optimum (rational) flame length implies a well-defined formulation of optimality criteria. In this respect a glass-melting furnace with a horseshoe-shaped flame is fundamentally different from a furnace with a lateral

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heating scheme. The requirements on the optimum flame length for a furnace with several pairs of burners can be formulated as two principal conditions. The first condition requires a maximum heat transfer from the flame to the tank surface providing for a maximum integral heat assimilation in the corresponding zone of the melting tank. The second condition depends on the requirement for uniform heating of the glass melt across the tank, in order to decrease the intensity of lateral convection flows in the melt. By finding a compromise between these mutually contradicting conditions one can determine the optimum flame length in furnaces with the lateral flame direction. This approach has been used by V. Ya. Dzyuzer [1] and later by other researchers as well [2].

For glass-melting furnaces with the horseshoe flame direction the condition of attaining a maximum heat transfer to the glass melt surface remains topical and, furthermore, is the main one for efficient fuel utilization. However, satisfying this requirement cannot be the deciding factor in solving the problem of the optimum flame length. One of the main functions of the flame in this type of furnaces is attaining a certain level of temperature and its distribution along the working space, to ensure the prescribed efficiency and glass melt quality. The temperature field of the gaseous medium and the refractory brickwork determines the temperature distribution on the glass melt surface. In specifying the temperature maximum, one has to meet at least two conditions. The first is to reach a prescribed furnace efficiency. The second one is to satisfy the temperature conditions for long-term safe operation of the upper refractory brickwork. None of the brickwork elements should have local overheating sites, which are typically found in furnaces with horseshoe-shaped flame.

Special attention should be paid to the formation of a temperature maximum on the glass melt surface. As was noted in [3], the current concepts of the quellpunkt position do not provide an unambiguous determination of its position in the melting tank. The boundary dividing the main convection flows in the specified type of the melting tank, even in the presence of a barrier, depends on the furnace operating regime as well, primarily on the furnace efficiency. The specifics of heating heaps of the batch in the initial phase of melting [4] suggests the advisability of increasing the multiplicity of the charging convection cycle. Thus, the desirable position of the quellpunkt ought to be selected taking into the account the hydrodynamics of the melt in the melting tank.

TABLE 1

Calculation variant	Characteristics of prescribed flame length*			
	l_i, m	l_f, m	l_i/L_f	l_f/L_f
1	3.178	4.544	0.233	0.334
2	6.300	9.010	0.462	0.662
3	9.534	13.634	0.700	1.000
4	11.580	16.560	0.850	1.216
5	13.620	19.480	1.000	1.430

* L_f is the length of the melting tank of the furnace equal to 13.62 m [5].

To summarize the above, one can say that the problem of the rational flame length for a glass-melting furnace with horseshoe flame implies jointly solving the exterior and interior heat exchange problems. It has become possible to set such a complex problem owing to the development of interrelated mathematical models of complex heat exchange in the working space of the furnace and in the melting tank. The analysis of exterior heat exchange implies using the resolvent zonal calculation method where boundary conditions of the second kind are specified on the glass melt surface and the temperature fields is the result of solving the exterior problem [5, 6]. The data of heat transfer calculation obtained under the boundary conditions of the first kind (temperature distribution being specified) [2, 7, 8] do not provide a complete picture of real heat exchange between the radiating gaseous medium, the upper brickwork, and the glass melt surface. This is primarily related to the impossibility of taking into account the heat consumed in endothermic glass-melting reactions and the compensation of heat loss via the tank brickwork, as well as a certain predictability of the distribution of resultant heat flows on the glass melt surface. Therefore, the earlier developed mathematical models of heat exchange [2, 7, 8] cannot be used to analyze the effect of the flame length on the thermal performance of the furnace.

In specifying a variable flame length, we used the concept of the "double-zone" air inflow in the combustion zone and the degree of fuel burn-out. This concept includes the notion of an intense combustion zone and an afterburning zone. The intense combustion zone (the visible part of the flame) is characterized by the inflow path length l_i that is related to the full flame length by the relation $l_f = 1.43 l_i$ [9]. The relative air inflow and the degree of fuel burn-out are calculated on the basis of the formulas given in [5]. The same paper offers a geometrical model of the furnace, the initial data, and the method for setting boundary modeling conditions.

Heat transfer calculations have been performed for five values of the flame length (Table 1). The choice of the calculation variants depends on the geometrical model of the working space of the furnace taking into account the technological melting zones. For instance, variant *1* implies that the extent of the intense fuel combustion area lies within the length of the tank surface occupied by batch heaps. In variant *2* the value l_i is equivalent the extent of the batch and foam zones. In the third variant the full flame length is equal to the furnace length and the visible part of the flame ends above the most probable quellpunkt location (0.7 tank length). The two last variants imply the afterburning of fuel during the reverse motion of the combustion products directed to the burner waste outlet. In this case the intense combustion zone is within the limits of the furnace length. Thus, all calculation variants may occur in practical operation of glass-melting furnaces with horseshoe-shaped flame.

Let us briefly consider the method for processing calculation results of zonal temperatures. In accordance with the geometrical model of the working space [5], the following averaging of zonal temperatures was performed for five calculation sectors along the furnace length. The mean temperatures of the gaseous medium, the roof surface, and the glass melt surface is obtained through averaging the temperatures of 15 volumetric and 5 respective surface zones identified for each calculation sector. Zonal temperatures were averaged using approximating continuous functions of the polynomial type. The degree of the polynomial was set lower by one than the number of zones whose temperatures were averaged. The distribution of average temperature along the furnace length was also approximated by polynomial functions.

The results of calculating the temperatures of the media participating in exterior heat exchange are shown in Fig. 1. They show a perceptible effect of the flame length on absolute temperature values and on their distribution along the longitudinal coordinate of the furnace. At the same time, we should note a certain disagreement with the traditional concept observed in the maximal temperatures of the gaseous medium for variants *1 – 3* compared to variants *4* and *5*. It could be expected that the shorter the flame length, the higher should be the temperature of its initial part. This regularity is clearly observed in furnaces with lateral flame [1, 2], but is not validated in the horseshoe-shape heating scheme. This is due to the fact that the results of temperature calculation depend perceptibly on the differential distribution of heat consumed in endothermic glass-melting reactions and glass melt heating specified via the source (outlet) summands of zonal equations of the surface melt zones. The first component of technological heat consumption is distributed among calculation sectors I – V as 1690.76, 1014.45, 507.23, 169.07, and 0.00 kW, respectively. Heat consumption within a calculation sector is proportional to the area of the surface glass melt zones. The consumption of the second component, where the heat outlet amounts to 71.228 kW/m^2 [5] is distributed in the similar way.

The high level of preset heat consumption in the batch and foam zones (calculation sectors I and II) prevents obtaining technologically adequate temperatures in the gaseous space, on the roof, or on the glass melt surface under short-flame fuel combustion (l_i/L_f = 0.233 – 0.462). The localization of intense heat release within the melting zone is characterized by a relatively low general temperature level, as well as highly heterogeneous temperature distribution (across the furnace) on the roof and on glass melt surface (Fig. 2), which is due not only to the asymmetric introduction of fuel (with respect to the longitudinal axis of the furnace), but also to the regularities of the formation of the aerodynamic flame contour. The longer the flame, the larger is the number of volumetric gaseous space zones involved in mass exchange with hot combustion products and the more homogeneous the temperature distribution across the width and height of the working space.

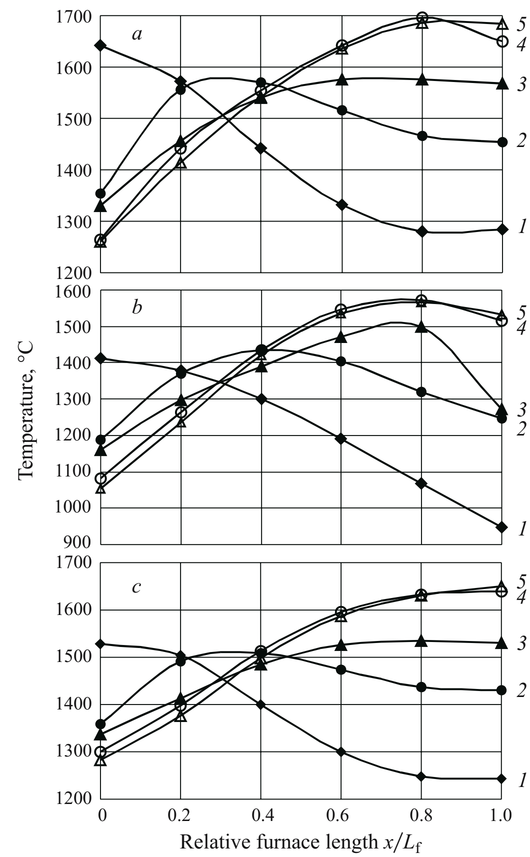

Fig. 1. The effect of flame length on the variation of the average temperature across the furnace for gaseous medium (*a*), glass melt surface (*b*), and roof (*c*): *1 – 5*) l_f/L_f = 0.334, 0.662, 1.000, 1.216, and 1.430, respectively.

Extending the zone of intense combustion (l_i/L_f = 0.70) makes it possible to increase the gaseous medium temperature in the refining zone and, accordingly, on the roof and on glass melt surface. The temperature field that is formed on the melt surface has clearly defined maximum temperature zones (Fig. 2). In general, the temperature curves obtained for the condition l_i/L_f = 0.70 appear the most technologically suitable, including as well the traditional concept of temperature distribution along the furnace. A further increase in l_f (Fig. 1, curves *4* and *5*) produces a substantial redistribution of heat emission along the furnace. In the initial sector of the furnace (the melting zone) the heat transfer from the flame is insufficient, whereas an evident excess of heat is observed in the clear glass melt zone. Note that changing l_i/L_f from 0.85 to 1.00 has no perceptible effect on the distribution and level of temperature. This regularity can be attributed to the minimal heat outlet via the glass melt surface in calculation sectors IV and V.

The data in Fig. 1 indicate a number of regularities characterizing the effect of the flame length on the exterior problem in the furnace with horseshoe-shaped flame. Thus, the average temperature distribution over the roof surface and the glass melt surface is virtually identical to the gaseous

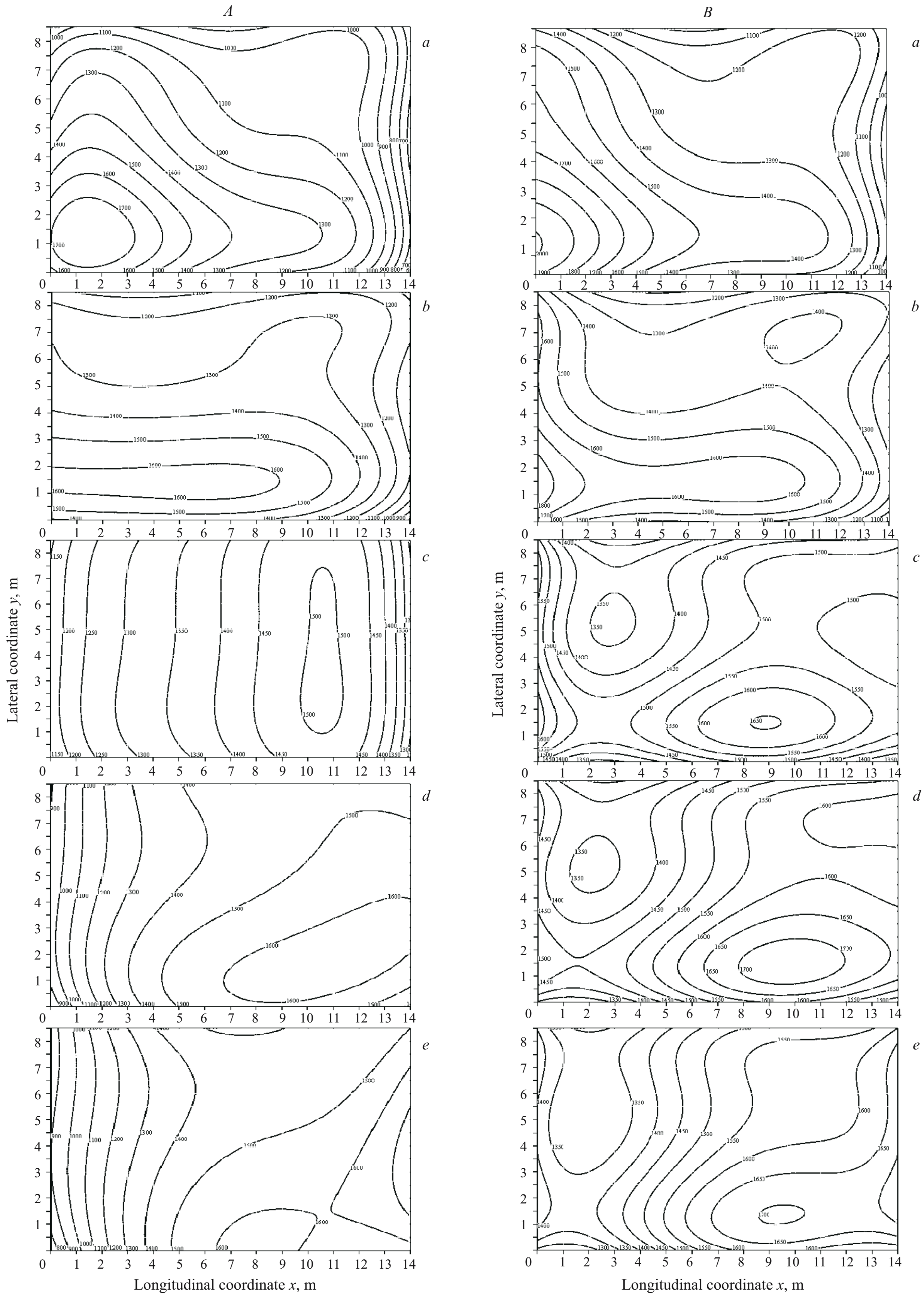

Fig. 2. The effect of flame length on the temperature fields of glass melt surface (*A*) and roof (*B*) for l_i/L_f equal to 0.334 (*a*), 0.662 (*b*), 1.000 (*c*), 1.216 (*d*), and 1.430 (*e*).

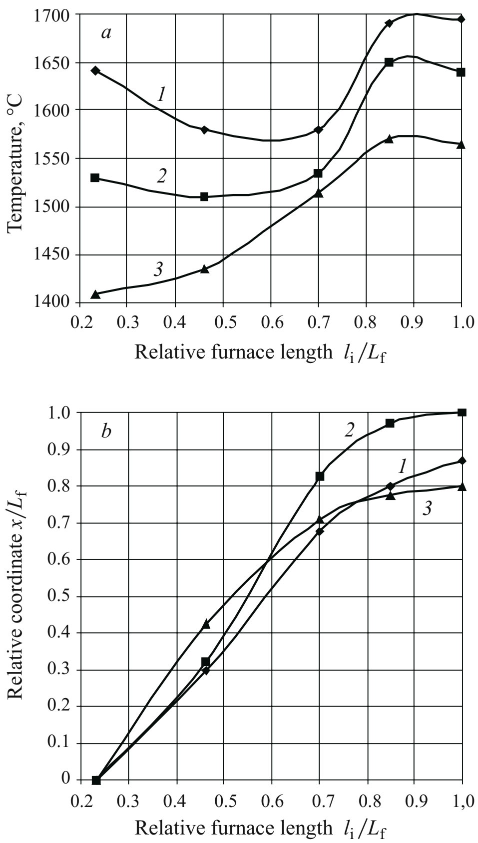

Fig. 3. The effect of the length of intense combustion zones l_i on the average maximum temperature across the furnace (*a*) and the location of the average temperature maximums across the furnace (*b*) for gaseous medium (*1*), roof surface (*2*), and glass melt (*3*).

space temperature curve. This dependence is largely true as well for the variation of the maximal value of average temperatures (Fig. 3*a*). Note a certain regularity in the variations in the difference between the maximum values of the mean temperatures of the gaseous medium and the heated surfaces. For the investigated values of l_i/L_f the temperature difference between the gaseous medium and the glass melt is equal to 232, 145, 65, 120, and 130°C and for the roof temperature — 112, 70, 45, 40, and 55°C. Thus, the minimal difference between the maximum temperatures of the gas space and the glass melt surface is $l_i/L_f = 0.70$ and between the roof surface and the melt it is 0.85.

In order to control the thermal performance of the furnace, it is essential to identify the position of the temperature maximum of the media along the working space. The data in Fig. 3*b* indicate the existence of certain regularities in the position of the maximum temperature depending on the flame length. First, it should be noted that at $l_i/L_f = 0.76$ we observe the coincidence of the temperature maximums of the gaseous medium and the glass melt surface. The longitudinal coordinate of this maximum is equal to $x/L_f = 0.76$, or the length of the intense combustion zone $x = l_i = 0.76L_f$. The second coincidence of the maximum temperature coordinate is observed for the brickwork and the glass melt; it corresponds to $l_i/L_f = 0.58$ and is characterized by $x = l_f = 0.58L_f$. Not that in both cases of curve intersections the length of the intense combustion zone coincides with the longitudinal coordinate of maximum temperatures. For $l_i/L_f = 0.70$, 0.85, and 1.00 the difference between the values x of the roof surface and the melt surface increases and is equal to 1.57, 2.67, and 2.72 m, respectively. If $l_i/L_f < 0.58$, then Δx has a negative value. For such flame lengths, the shift in the coordinate of the maximum temperature of the glass melt along the longitudinal axis is more significant than in the roof surface temperature.

The analysis of the calculations of exterior heat exchange suggests a preliminary conclusion that based on the set of revealed regularities the advisable length of the flame should meet the condition $l_f/L_f \leq 1.0$. Consequently, the extent of the intense combustion zone (the visible part of the flame) should be equal to approximately 0.7 melting tank length.

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